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Techno-Economic Analysis of Hemp Production, Logistics and Processing in the U.S

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Abstract: Industrial hemp is a versatile crop, and its products have important applications in the food, cosmetic, pharmaceutical, textile, paper and composite industries. Since its legalization in the U.S. in 2018, interest in growing and using hemp has been increasing. This study evaluated the techno-economics of hemp grain and fiber production, harvest and post-harvest logistics, the drying and storage of hemp grain, and the decortication of fiber stalks. The analysis was performed using a process modeling approach with data obtained from the literature considering a farm size of 162 ha (average U.S. farm size). The input parameters were used as distributed functions and the results obtained are reported as interquartile ranges after 10,000 Monte Carlo simulations. The total cost of producing and processing hemp grain and fiber was estimated to be in the interquartile range of USD 2911–3566 Mg^{-1} and USD 1155–1505 Mg^{-1}, respectively. The costs of seed and fertilizer along with grain and fiber yields were found to be the major factors influencing field production costs, while costs associated with facilities and labor were the main costs in fiber processing. Despite the high resource requirements and processing costs, high-value applications of hemp grain and fiber show great potential to produce net incomes of USD 426–3701 Mg^{-1} and USD 1570–2016 Mg^{-1}, respectively.

Keywords: hemp grain; natural fiber; systems analysis; logistics

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1. Introduction

The U.S. market for hemp grain and fiber, a sustainable crop [1] with several applications [2], is expected to increase at a rate of 17.1% from 2023 to 2030, with an expected value of USD 16.75 billion [3]. Since its legalization in the 2014 and 2018 U.S. Farm bills, interest in growing and utilizing industrial hemp has been expanding. Different varieties of hemp are cultivated for CBD (cannabidiol) oil, grain, or fiber, while some varieties can produce both fiber and grain. CBD oil is the highest-value product produced from the hemp flower and is commonly used for treating physical as well as mental illnesses [4]. In 2022, 3082 megagrams (Mg) of floral hemp was produced in the U.S., with an estimated value of USD 179 million [4]. However, the CBD hemp market has been saturated due to high producer participation [4]. There is a need to increase the production of multiple varieties of hemp for different uses.

Hemp is a temperate crop that can be grown for fiber and grain in many U.S. states [5]. In 2022, hemp grain production was highest in Midwestern states (1383 ha), followed by Northwestern states (396 ha) [4]. Hemp fiber production was also most concentrated in the Midwest, mainly Missouri (526 ha) and South Dakota (324 ha), followed by Montana (255 ha), Virginia (194 ha), North Carolina (170 ha), Kentucky (73 ha) and Oregon (40 ha) [4]. In 2022, the total hemp grain production was 1104 Mg, worth USD 3.6 million, while hemp fiber production was 9545 Mg, worth USD 28.3 million [4]. Due to the market saturation of hemp grown for CBD, there is increasing interest in growing hemp in rotation with other major grains such as corn, soybean, and other oilseed crops that are used for grain and fiber. Hemp grain and fiber have high-value applications in food and textile industries [6]. Hemp grain is sold as a dietary supplement, due to its nutritional benefits [7]. Similarly, there are several applications of hemp fiber, including construction and building materials, textiles, and paper [8,9]. In addition, to encourage more producers to grow hemp for grain and fiber, new federal laws are being written that reduce the THC content restrictions for grain and fiber hemp varieties [10].

Current research on hemp is focused on establishing agronomy for hemp production methods and other best management practices for hemp harvest and storage for different hemp varieties [11–15]. These practices include determining optimal growing degree day requirements, field preparation, seeding rates, row spacing, nutrients requirements, harvest timing, and potential yield [12–18]. These studies have found that early-maturing varieties are better for fiber production while late maturing varieties are better for seed production [17,18]. However, grain loss due to seed shatter is a major concern for grain production, thus the optimal harvest timing is at a seed maturity of ~70% and a grain moisture between 22 and 30% [12,17]. In addition, research on herbicides and pesticides for hemp is ongoing.

A few studies have evaluated the economic viability of hemp production. One study considered intercropping fiber hemp with loblolly pine for 6 years during its establishment in the Southwestern U.S. It estimated that such a system could produce 25% higher overall returns for the farm compared to monocropping of loblolly pine [19]. Another study in the Czech Republic evaluated the economics of using the residual biomass from CBD hemp production for energy or biochar and found that the cost of biochar or direct use of hemp biomass for energy would be less than other biomass grown solely for bioenergy [20]. However, this study allocated the cost of field production completely to the flowers, and only considered the costs associated with collecting and processing the residual biomass. One study, which evaluated the economic viability of industrial hemp production in Turkey, estimated the hemp stalk production costs for hemp fiber alone and a dual purpose (fiber and grain) at USD 0.29 kg^{-1} and USD 0.41 kg^{-1}, respectively [21].

These economic analyses have mostly been conducted using linear programming, directly using costs and prices from the literature. However, a comprehensive systems analysis using process modeling has not been conducted for the Midwestern U.S., where hemp grain and fiber production is increasing [4]. Thus, the main objective of this study is to determine the technical feasibility and costs of hemp grain and fiber production, harvest and post-harvest logistics, and processing for the Midwestern U.S. This study incorporates current agronomic and best management practices and state-of-the-art technology for harvest and post-harvest logistics and processing.

2. Materials and Methods

2.1. System Definition

The system considered for the analysis consisted of all processes required for the field production, harvest, post-harvest collection and handling of hemp grain and stalks, the drying and storage of hemp grain, and the storage and decortication of hemp stalks (Figure 1). The functional unit for the analysis was considered to be 1 Mg of hemp fiber and grain produced. For field production, seeding and fertilization were considered and it was assumed that pesticide application and irrigation were not necessary [22]. The farm size used for both hemp grain and fiber production scenarios was 162 ha because the average farm size in the U.S. has been in the range of 177 to 180 ha since 2014 [23]. While this size is bigger than 49 ha, which was the average size of actual hemp farms in the U.S. in 2019 [24], most of these farms produced high-value hemp varieties for CBD. Thus, for this model, which considered grain and fiber production, which have a lower economic value than hemp flowers, the 10-year average U.S. farm size was used.

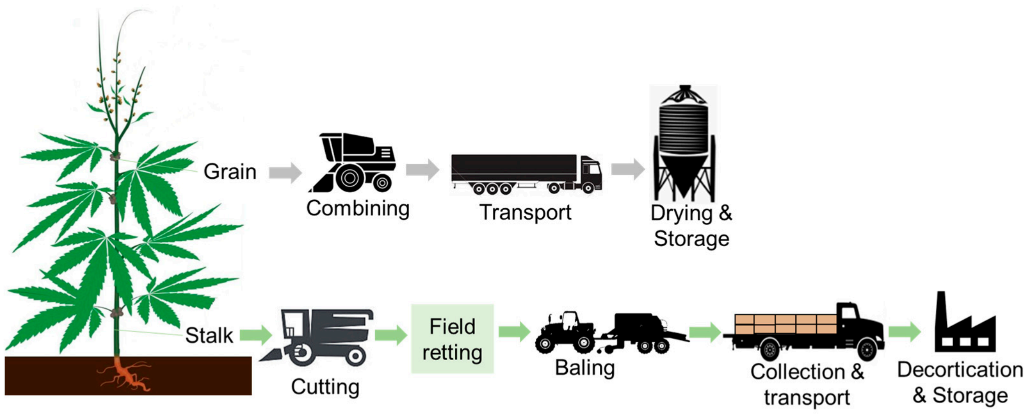

Figure 1. System boundary considered for hemp grain and fiber production, harvest, and post-harvest logistics and processing.

2.2. Discrete Production Processes

2.2.1. Field Production

For the field production of hemp grain and fiber, direct seeding was considered and seeding rates are provided in Table 1. Nitrogen, phosphorus and potassium fertilizer applications for both hemp grain and fiber stalks were based on recommendations from the literature.

Table 1. Agronomic parameters considered for the analysis *.

Parameters	Unit	Grain	Fiber
Seeding			
Optimal planting density	plants ha^{-1}	1,347,385 (1,075,932–1,613,898) [25]	3,496,779 (3,227,796–3,765,762) [18]
Germination rate	%	45% (10–80%) [13]	83% (70–91%) [26]
Hemp seeds weight	g 1000 kernels^{-1}	20 (18–22) [12]	20 (18–22) [12]
Fertilizer			
Nitrogen	kg ha^{-1}	157 (64–168) [14,17,27]	168 (112–225) [14,17]
Phosphorus	kg ha^{-1}	38 (15–64) [14,17,27]	45 (22–90) [14,17]
Potassium	kg ha^{-1}	43 (19–64) [14,17,27]	84 (22–225) [14,17]
Yield	kg ha^{-1}	339 (285–393) [5]	2620 (2140–4773) [5,28,29]

* The values represent the triangular distribution of the parameters with the average, minimum, and maximum values in parenthesis.

Seeding: Seeding was considered to be completed using a 4.5 m drill planter for both grain and fiber hemp. The inter-row spacing for grain hemp was considered to be 0.4 m [25], and for fiber hemp it was considered to be 0.3 m [12], based on agronomic practices. Due to the larger inter-row spacing for grain hemp, the planting density was lower per acre than that for fiber hemp (Table 1). The seeding rate was estimated using the optimal planting density, germination rate, and 1000 kernel weight of hemp seeds (Table 1). The field productivity of the seeding equipment was estimated using the seeding width, speed, and field efficiency (Table 2). The field efficiency used was based on literature values and is similar to the ASABE standard [30], which is widely used for making machinery management decisions for farm operations in the U.S. Since field conditions vary greatly due to variations in topography, it is important to use a more generic field efficiency that can be applicable to a wider geographic region as the same equipment will function differently on different fields. This was considered for all operations and is not specific to the seeding operation.

Table 2. Equipment parameters used for the different operations considered for the analysis.

Equipment Parameters	Unit	Values *	Assumption #
Seeding			
Speed	km h^{-1}	9.6 (6.4–12.8) [31]	Rated speed
Field efficiency	%	70%	Based on literature [32]
Power	kW	75 [33]	Rated power
Fertilization			
Speed	km h^{-1}	9.6	Based on literature [32]
Field efficiency	%	70%	Based on literature [32]
Power	kW	30 [34]	Rated power
Harvest and post-harvest			
Grain harvest			
Combine speed	km h^{-1}	6.4 (4.8–8.0) [35]	Rated speed
Combine field efficiency	%	77% (75–78%)	Based on literature [32]
Combine power	kW	68.25 [35]	Rated power
Grain cart storage capacity	m^3	26.4 [36]	Rated capacity
Grain cart tractor power	kW	112.5 [36]	Rated power
Grain cart unload speed	m^3 s^{-1}	0.29 [36]	Rated capacity
Fiber harvest			
Mower width	m	2.1 [37]	Rated width
Mowing speed	km h^{-1}	11.2	Based on literature [32]
Mower field efficiency	%	80% (78–83%)	Based on literature [32]
Windrower width	m	2.7 [38,39]	Rated width
Windrowing speed	km h^{-1}	6.4 (4.8–8.0)	Based on literature d [32]
Windrowing field efficiency	%	79% (78–80%)	Based on literature [32]
Baling width	m	2.7 [40]	Rated width
Baling speed	km h^{-1}	4.8 (3.2–6.4)	Based on usual practice [41]
Baling field efficiency	%	80% (70–90%)	Based on literature [32]
Bale handling capacity	no. $load^{-1}$	12 [42,43]	Rated load capacity
Bale handler transport speed	km h^{-1}	9.6 (8.0–11.2) [43]	Rated speed

* Multiple values for the same parameter represent its triangular distribution with the average, minimum, and maximum values in parenthesis. # For speed and field efficiency of different operations, values were either obtained from the literature or based on the specification of the equipment used in this analysis.

Fertilization: Dry fertilizers were considered for both grain and fiber hemp production at the recommended rates (Table 1). Urea was used as the source for nitrogen, di-ammonium phosphate (DAP) for phosphorus, and potassium chloride for potassium. Fertilization was considered to be applied using a dry fertilizer spreader with a 0.45 Mg capacity and spreading width of 1.2 m. The productivity of the fertilizer spreader was estimated based on field speed, field efficiency, spreading width, and fertilizer holding capacity (Table 2).

2.2.2. Harvest and Post-Harvest Logistics

Grain harvest and transport: Combining was considered for harvesting hemp grain, as it is the most common grain harvesting method in the U.S. Due to the small size of the farm, a 2-row plot combine (1.7 m), with a storage capacity of 1.4 m^3 and an unloading rate of 58 kg s^{-1}, was considered for harvesting the hemp grain. The productivity of the combine was calculated based on the field speed, working width, and field efficiency. A small grain cart, with a 26.4 m^3 storage capacity, was considered for collecting and transporting the hemp grain from the field to the field edge for drying and storage. The speed of the grain cart was considered to be 6.4 km h^{-1} for collection and transportation. For the transportation distance, the farm was considered to be circular, with the radius used as the transport distance.

Fiber harvest: Hemp stalk harvesting for fiber was considered to be achieved using a multi-pass system consisting of mowing, windrowing, baling, and collecting and stacking bales at the field edge. Mowing was considered to be performed at a hemp moisture content of 30% for field retting [44], in which hemp is left in the field until the stalk dries to a moisture content of 15% [45]. It was assumed that the hemp fiber yield was 20–30% of the hemp stalk [46]. Thus, the amount of material to be mowed, windrowed, and baled was estimated based on the total hemp stalk yield. Windrowing was considered to be performed after the hemp had field retted for two weeks [45].

Baling was considered to be performed after windrowing using a large rectangular baler. The number of bales to be formed was estimated based on the hemp stalk yield. The wet bulk density of the bales was considered to be in the range of 176–224 kg m^3 based on the bulk density achieved for other biomass bales, and the bale dimensions used were 0.9 m $\times$ 1.2 m $\times$ 2.4 m. Bale collection and stacking at the field edge were considered to be performed using a bale handler that can collect and transport 12 bales per trip. For the transportation distance between the field edge and the bales, the farm was considered to be circular, with its radius used as the average transport distance.

2.2.3. Storage and Processing

Grain: Grain was considered to be stored in a silo at the farm. Since grain was to be harvested at 15% average moisture content (12–20% range) [45] and safe grain storage was at 8% [45], grain drying prior to storage was necessary. The energy required for grain drying was estimated to be 34–56 MJ Mg^{-1} of grain and was based on the amount of water that needed to be removed to reach 8% moisture. It was assumed that hemp grain drying and storage would be performed using existing systems used for other grains such as corn and soybean.

Fiber: Hemp stalks require decortication to separate the outer bast fiber from the inner hurd. Decortication and baling of the hemp fibers was considered for the processing of hemp stalks. Processing of hemp fibers was considered to be performed on farm; thus, a small scale decortication system was considered for the analysis [47]. This system also included conveying, cleaning, and sorting of the bast fiber and hurd post-decortication. The decorticating capacity of the system was 454 kg h^{-1} and its power requirement was 7.5 kW based on a similarly sized decorticating unit [48]. To facilitate the post-process handling and transportation of hemp fiber bales, a stationary compacting unit with a productivity of 4–6 bales h^{-1} was considered [49]. The bales were considered to be 80–120 kg by weight and their dimensions were 0.8 m $\times$ 0.4 m $\times$ 0.8 m [49]. The power requirement of the unit was 4 kW [49]. The operating hour requirements of the processing plant were estimated based on the productivity of the processing equipment, which were also used to estimate the total power and labor hour requirements.

2.3. Economic Considerations

Consumables and labor: The major cost inputs required for this study, excluding the capital cost of equipment, were the land rental cost; the price of consumables including seeds, fertilizers, and fuel; and farm labor wages (Table 3). License fees for growers and processors were not included because this fee would be negligible over time for the farm size and the service life considered in the analysis [50]. For grain, on-farm drying and storage costs were also considered [51] and were assumed to be the same as current commercial grain drying and storage costs (Table 3). The labor requirement for the field operations were estimated to be 1.2 times the actual machinery hours in the field [52]. Fuel use for the different operations was estimated using the rated power required for the operation (Table 2) and a specific fuel consumption coefficient of 0.015 l kW-h^{-1} (0.044 gal hp-h^{-1}) [53], as well as the total hours used every year.

Table 3. Price of fertilizers, fuel, and other inputs to the model.

Parameters	Units	Values *
Land rental cost	USD ha^{-1}	563 (452–674) [54]
Urea ammonium nitrate (UAN) **	USD Mg^{-1}	658 (599–732) [55]
Diammonium phosphate (DAP) **	USD Mg^{-1}	835 (818–868) [55]
Potash **	USD Mg^{-1}	672 (623–742) [55]
Diesel price ***	USD l^{-1}	1.07 (1.00–1.16) [56]
Hourly wage for field workers ****	USD h^{-1}	17.77 (17.64–17.89) [57]
Grain drying costs	USD Mg^{-1}	0.15 (0.10–0.21) [51]
Grain storage costs	USD Mg^{-1}	10.91 (5.91–15.91) [51]
Hourly wage for production workers	USD h^{-1}	17.06 (13.23–27.01) [58]
Hemp grain selling price	USD kg^{-1}	3.32 (1.45–12.25) [5]
Hemp fiber selling price	USD kg^{-1}	3.30 (2.64–3.96) [5]

* Values for each parameter represent the triangular distribution with the average, minimum, and maximum values in parenthesis. ** Nitrogen, phosphorus, and potassium fertilizers prices were from late 2022 to early 2023. *** Average diesel price was from 2023. **** Labor wages from 2022 were used for the field workers with 30% benefits.

Equipment: The costs of the different pieces of equipment were obtained from the manufacturers' websites (Table 4). The actual purchase price of the equipment was assumed to be 85% of the list price [52]. The annualized cost, salvage value, and annual repair and maintenance cost of the equipment were estimated using equations from ASABE standards [59,60] and factors listed in Table 4 [60]. In addition, other relevant costs, including taxes, housing, insurance rates, and lubrication, were based on the annualized equipment cost and are summarized in Table 4.

Table 4. Purchase price of field equipment and factors for estimating annual fixed costs.

Parameters	Units	Values *
Factors applicable to all equipment		
Interest rate **	%	9.5 (9.0–10.0) [61,62]
Taxes, housing and insurance rate	%	2% [60]
Lubrication cost as percent of fuel cost	%	15% [60]
Tractor		
Tractor list price (131.25 kW)	USD	219,654 (183,800–269,161) [63–65]
C1, C2, C3 ***		0.976, 0.119, 0.0019
Service life	hours	16,000
RF1, RF2 ***		0.003, 2
Grain drill		
Grain drill list price (75 kW)	USD	51,100 (37,500–69,900) [66–68]
C1, C2		0.943, 0.111
Service life	hours	5000
RF1, RF2		0.41, 1.3
Fertilizer spreader		
Fertilizer spreader list price (30 kW)	USD	3599 (2879–4319) [69]
C1, C2		0.943, 0.111
Service life	hours	1000
RF1, RF2		0.41, 1.3
Combine		
Combine list price (68.25 kW)	USD	550,000 (440,000–660,000)
C1, C2, C3		1.132, 0.165, 0.0079
Service life	hours	5000
RF1, RF2		0.12, 2.3

Table 4. *Cont.*

Parameters	Units	Values *
Grain cart		
Grain cart list price (112.5 kW)	USD	61,900 (49,520–74,280) [70]
C1, C2		0.943, 0.111
Service life	hours	5000
RF1, RF2		0.41, 1.3
Mower		
Mower list price (28.12 kW)	USD	7178 (5742–8613) [37]
C1, C2		0.756, 0.067
Service life	hours	5000
RF1, RF2		0.44, 2
Windrower		
Windrower list price (54.37 kW)	USD	35,875 (34,850–36,900) [71,72]
C1, C2		0.791, 0.091
Service life	hours	5000
RF1, RF2		0.03, 2
Baler		
Baler list price (131.25 kW)	USD	192,998 (169,900–253,900) [73–76]
C1, C2		0.852, 0.101
Service life	hours	3000
RF1, RF2		0.1, 1.8
Bale loader		
Baler loader list price (112.5 kW)	USD	173,500 (138,800–208,200) [77]
C1, C2, C3		0.943, 0.111
Service life	hours	5000
RF1, RF2		0.41, 1.3

* Equipment list prices were obtained from different manufacturers' websites and represent the triangular distribution with the average, minimum, and maximum values in parenthesis. ** The interest rate used accounted for the current interest on farm loans and the average inflation rate for 2023. It is represented as a triangular distribution with the minimum and maximum values in parenthesis. *** Salvage value coefficients (C1, C2, C3) and repairs and maintenance coefficients (RF1, RF2) were obtained from the ASABE standard [60].

Processing: Processing costs for hemp fiber stalks were estimated based on the purchase price of the equipment and the factors for building the processing facility based on the equipment price, as provided in Table 5. The annual facility-dependent cost was estimated based on the service life of the plant and the interest rate.

Table 5. Processing equipment purchase price and facility cost factors.

Parameters	Units	Values *
Equipment purchase price		
Decorticator assembly	USD	229,000 [47]
Stationary fiber compactor	USD	10,000 [49]
Factors for estimating facility cost *		
Interest rate **	%	9.5 (9.0–10.0) [61,62]
Direct cost (DC)		
Total Equipment purchase cost (TP)		239,000
Instrumentation as % of TP	%	15
Electrical as % of TP	%	5
Buildings as % of TP	%	10
Yard improvement as % of TP	%	5

Table 5. *Cont.*

Parameters	Units	Values *
Indirect cost (IDC)		
Engineering as % of DC	%	10
Construction as % of DC	%	10
Miscellaneous cost (MC)		
Contractor's fee as % of DC + IDC	%	5
Contingency as % of DC + IDC	%	5
Direct Fixed Capital (DFC)		DC + IDC + MC
Repair and maintenance as % of DFC	%	3
Taxes and insurance as % of DFC	%	1
Salvage value as % of DFC	%	11
Service life of the plant	years	30

* The factors required to estimate the cost of processing facility were based on the factors in the SuperPro Designer process modelling software [78]. Due to the less complicated nature of the processing facility, the factors associated with direct fixed capital were reduced by at least 50% for each category. Taxes and insurance were kept the same. ** The interest rate used accounted for the current interest on farm loans and the average inflation rate for 2023. It is represented as triangular distribution with average, minimum, and maximum values in parenthesis.

2.4. Uncertainty and Sensitivity Analyses

The input parameters were used as distribution functions due to the uncertainty associated with them. The distributions considered were mostly triangular due to limited data availability. Monte Carlo simulations (10,000 iterations) were performed to obtain the distribution of the outcomes and are reported as interquartile (IQR) ranges. In addition, sensitivity analysis was conducted to identify the most influential parameters that affect the outcomes of the analysis.

3. Results and Discussion

3.1. Feedstock Production and Fertilizer Requirement

The grain and fiber produced from the 162 ha farm had an IQR of 128–141 and 487–647 t/year, respectively. Hemp grain yields were lower than hemp fiber yields. However, hemp grain is considered a superfood and could be used for higher-value applications than processed hemp fiber, which could make hemp grain more attractive for farmers. With the implementation of the best management practices, hemp grain and fiber yields are likely to increase in the future.

Hemp grain required 206–284 kg Mg^{-1} of urea for nitrogen, 57–109 kg Mg^{-1} of DAP for phosphorus, and 49–85 kg Mg^{-1} of potash for potassium. For hemp fiber, 62–87 kg Mg^{-1} of urea, 22–34 kg Mg^{-1} of DAP, and 30–55 kg Mg^{-1} of potash were required. For comparison, the fertilizer requirement for hemp production is higher than that of the major row crops in the U.S. (corn: 60 kg Mg^{-1} of urea, 12 kg Mg^{-1} of DAP and 28 kg Mg^{-1} of potash [79]; soybean: 14 kg Mg^{-1} of DAP and 23 kg Mg^{-1} of potash [80]) due to the lower hemp grain and fiber yields (Mg ha^{-1}).

3.2. Machinery, Fuel and Labor Requirements for Field Operations

For the modeled 162 ha farm size, for both hemp grain and fiber production, one of each piece of equipment for different operations was enough to fulfill the machinery needs. However, for smaller farms, i.e., 49 ha [25], which is the current median hemp farm size in the U.S., it would not be economic for a farmer to own all the equipment; thus, hiring custom operators would be the most viable option.

Machinery hour, fuel, and labor requirements are summarized in Table 6. Machinery hour requirements for the seeding of grain and fiber hemp were similar, as the productivity of the grain drill was assumed to be the same. The slightly higher number of hours required for fiber hemp is due to the higher number of trips required for refilling the grain drill during planting as the seeding rate for fiber is higher. A similar trend was observed for fertilization because of the higher fertilizer requirements for fiber hemp per hectare.

Combine harvesting was considered for grain while mowing, windrowing, and baling were considered for fiber stalk harvesting. The number of grain harvesting, collection, and transportation hours was high because a small plot combine was considered for harvesting grain hemp, while the grain cart would transport the grain to the field edge for storage. Due to the small width of the plot combine, the number of harvesting hours was high. If a large combine was considered, the field productivity of the combine would be much higher than the plot combine considered here. However, since the scale of operation considered in this analysis was small, a plot combine was considered to be suitable. Fiber harvest hours were also high compared to other field operations because of the multiple operations required, including mowing, windrowing, and baling, which increased the total number of harvesting hours. The collection and transportation of the hemp stalk bales were considered to be performed using an efficient bale collector and stacker, and thus had lower machinery hour requirements. The fuel use for grain and fiber production and harvesting and labor hour requirements followed a similar trend to machinery hour requirements.

Table 6. Machinery hours, fuel (diesel) and labor hour requirements for hemp grain and fiber production, harvesting and post-harvest logistics *.

Machinery Hours (h year^{-1})	**Grain**	**Fiber**
Tractor—seeding	68 (60–74)	68 (61–74)
Tractor—fertilization	117 (115–120)	129 (126–132)
Combine—grain harvest	198 (183–212)	
Tractor—stalk harvest		241 (227–253)
Tractor—collection and transport	207 (192–221)	63 (52–71)
Total machinery hours	*590 (559–618)*	*500 (482–517)*
Fuel (Diesel) (l year^{-1})	**Grain**	**Fiber**
Seeding	1128 (1007–1227)	1131 (1010–1231)
Fertilization	783 (768–798)	859 (838–881)
Harvest	3009 (2772–3214)	4490 (4115–4807)
Collection and transport	5184 (4791–5526)	1591 (1328–1809)
Labor Hours (h year^{-1})	**Grain**	**Fiber**
Seeding	81 (72–88)	81 (73–89)
Fertilization	141 (138–144)	155 (151–158)
Harvest	238 (219–254)	289 (273–304)
Collection and transport	249 (230–265)	75 (63–86)

* Values reported as the average and IQR in parenthesis.

3.3. Hemp Fiber Stalk Processing Resource Requirements

Hemp stalk processing requirements were estimated in terms of energy, labor, and equipment requirements. One decorticator (454 kg h^{-1}) and one stationary baling unit (4–6 bales h^{-1}) with the rated processing capacities would be sufficient to process the amount of hemp stalks produced from the 162 ha farm considered in this analysis. The total number of equipment hours required for processing was estimated to be in the IQR of 1084–1437 h year^{-1}, which is equivalent to 3.6–4.8 months per year, with the decorticator and stationary baling unit working simultaneously. This type of facility would be similar to cotton gins in the U.S., which typically operate for 1–2 months of the year, and remain idle for the rest of the year [81]. Having an on-farm processing unit to process the hemp stalk could provide employment for farm workers beyond the harvest period, which would be beneficial for the rural economy. It was assumed that one full-time worker would be able to complete the processing tasks, as the decorticator and stationary baling units considered are fully automated. The worker would be required to monitor the processing equipment and move the materials. All processing was considered to be performed using electricity and the energy requirements for hemp stalk processing for the farm size considered were estimated to be in the IQR of 12,075–16,010 kWh year^{-1}.

3.4. Hemp Grain and Fiber Production Cost

The total cost of hemp grain production, harvesting, post-harvest logistics, and drying and storage was estimated to be in the IQR of USD 2913–3573 Mg^{-1} (Figure 2a). The total cost of hemp fiber production, harvest, post-harvest logistics, and processing was estimated to be in the IQR of USD 1155–1505 Mg^{-1} (Figure 2b). Hemp fiber production and processing costs were lower than grain costs because of the lower fertilizer requirements and higher fiber yields. For grain hemp, the cost of consumables, i.e., seeds and fertilizers, contributed 50% of the total production cost, followed by equipment (23%), land rental (21%), labor (4%), and fuel (2%). Similarly, for fiber hemp, consumables, i.e., seeds and fertilizers, contributed 59% of the total production cost, followed by equipment (20%), land rental (12%), labor (7%), and fuel/energy (1%). The cost of the seeds contributed 94% and 95% of the total seeding cost for grain and fiber hemp, respectively, due to the current low hemp seed production, as the crop is in its infancy. With the increase in hemp seed production and price stabilization, it is likely that the cost of hemp seeds will be reduced, thus reducing the overall cost of production. Fertilization operations followed a similar trend as fertilizer prices have increased drastically since 2020 [82] due to rising inflation, and hemp grain and fiber have higher fertilizer requirements, while producing lower yields compared to conventional crops such as corn (14 Mg ha^{-1}) and soybean (4.7 Mg ha^{-1}).

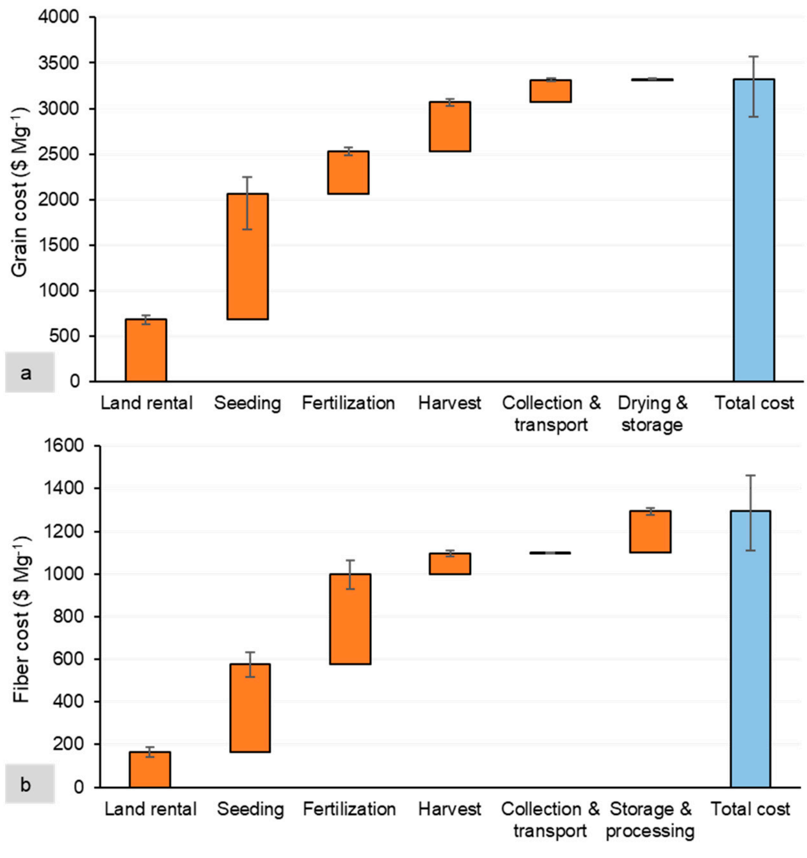

Figure 2. Cost breakdown of hemp grain (**a**) and fiber (**b**) production, logistics, storage and processing.

For harvest and post-harvest logistics, equipment cost was the highest contributor for both grain and fiber hemp. This was due to the use of capital-intensive farm equipment, which has high productivity but is fully automated with low labor requirements. For grain hemp, the harvest cost alone contributed to 16% of the total cost due to the high cost of the combine. For fiber hemp, harvest and post-harvest logistics had a lower contribution of 11% because of the use of existing equipment, which is less expensive and efficient for biomass cutting and baling.

The contribution of grain hemp drying and storage to the total cost was low because grain drying and storage are already commercially available. It was assumed that the cost of grain hemp drying and storage would be same as that for commercial facilities. For fiber hemp processing, facility-related costs contributed 63% of the total cost, followed by labor (36%) and energy (1%). The contribution of facilities and labor was significant because of the small size of the processing plant and the high cost of the processing equipment. As hemp stalk processing equipment is in its infancy, only a few companies manufacture the processing equipment, and the related costs are high. Because the amount of material for a 162 ha farm requires only 3.6–4.8 months for processing, the excess equipment capacity would allow the processing of additional material in this facility. Thus, if more material is processed, the facility and labor needs will not increase in the same proportion due to economy of scale, which can help reduce the total processing costs. However, collecting more material will result in a larger collection radius around the processing plant, increasing the transport distance between the field and the plant, which can increase the post-harvest logistics cost.

3.5. Income from Hemp Grain and Fiber

Based on the current market prices of hemp grain and fiber, the average net income for the 162 ha farm considered was estimated to be USD 325,212 year^{-1} (IQR: USD 62,671–551,136 year^{-1}) for hemp grain and USD 1,162,115 year^{-1} (IQR: USD 874,421–1,412,350 year^{-1}) for hemp fiber, respectively. For the same farm size, corn and soybean would have generated a net income of USD 53,200–200,000 year^{-1} and USD 46,400–128,400 year^{-1}, respectively, considering high corn and soybean yields of 14 and 4.7 Mg ha^{-1} and higher-than-average prices of USD 262 Mg^{-1} and USD 530 Mg^{-1}, respectively [83]. The higher estimated income for hemp grain is due to its market price (USD 3.32 kg^{-1}) [5], which is 13 and 6 times higher than that of corn (USD 0.26 kg^{-1}) [83] and soybean (USD 0.52 kg^{-1}), respectively [83]. Similarly, the price of hemp fiber (USD 3.3 kg^{-1}) [5] is two times higher than other natural fibers such as cotton (USD 1.87 kg^{-1}) [84].

Despite the potential to produce a higher income for the farmers, the resource (seeds, fertilizers) requirements for the production of hemp grain and fiber are high compared to existing crops, as hemp is new to farmers in the U.S. Due to the newness of hemp products and markets, prices are volatile, thus there is risk that the income generated could be lower. Similar to the decrease in CBD biomass prices over the last few years [85], it is likely that hemp grain and fiber prices will decrease as their production increases. Thus, the results from this analysis would be applicable for the current state of technology and for the current costs and prices, which are likely to change in the future as hemp markets develop, and thus market volatility is the main limitation of this study. In addition, the environmental impacts of hemp grain and fiber production and processing need to be evaluated and compared to existing ones. However, this study can provide direction to farmers and processors that are interested in hemp but are hesitant due to unknown associated costs.

3.6. Sensitivity Analysis

Sensitivity analysis was conducted to identify the parameters that were most influential on the net income. The price of hemp grain and fiber were the most influential parameters as there is currently high variability in their price due to the volatile market (Figure 3). Other influential parameters were associated with seeding and fertilization, including the germination rate, plant population, and fertilizer application rate, as these operations were among the highest contributors to the production cost, which would negatively influence the net income obtained. In addition, hemp grain and fiber yields also had a high influence on the net income, as the yield can directly increase/decrease the net income. For grain hemp, land rental cost was also one of the most influential parameters as it contributed more than 20% of the cost. Farmers and processors, as well as other researchers, can use this sensitivity analysis as a starting point, which identifies the major hotspots within the system in the current context. This will provide direction for future research as the system needs to be optimized for the field production of both grain and fiber hemp and the processing of the fiber stalks.

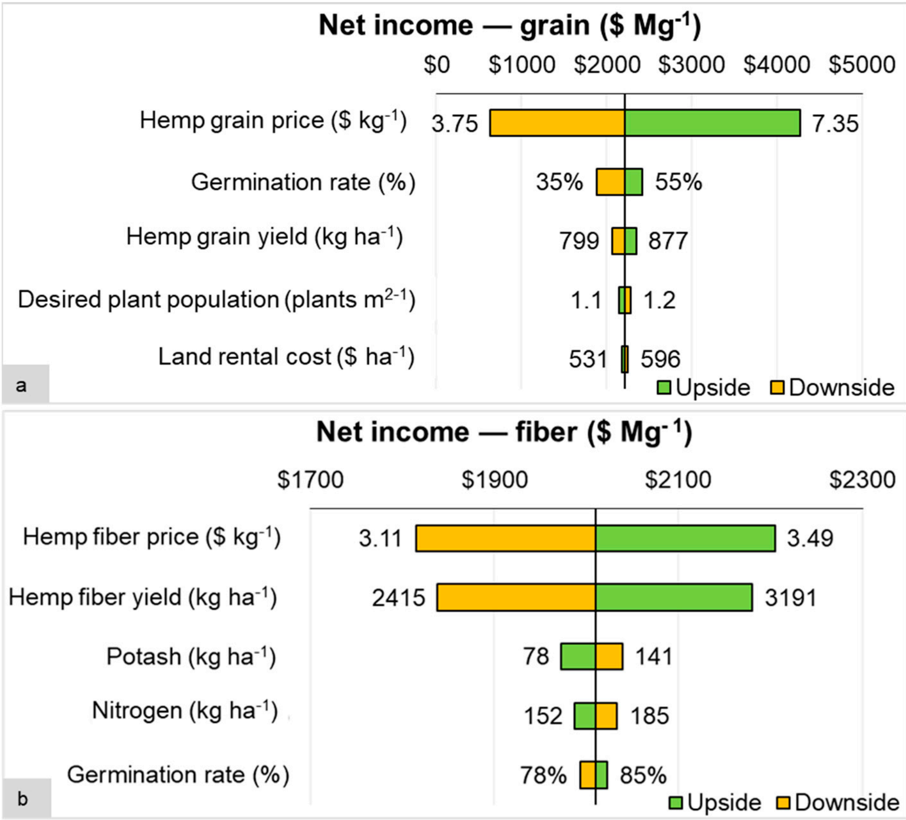

Figure 3. Sensitivity analysis chart for net income from hemp grain (**a**) and fiber (**b**) production and processing. (Note: Numbers in the chart represent interquartile range of parameters).

4. Conclusions

The techno-economics of hemp grain and fiber production and processing for an average U.S. farm size of 162 ha was evaluated. The total cost of hemp grain and fiber production, harvest, post-harvest logistics, and processing was estimated to be USD 2913–3573 Mg^{-1} and USD 1155–1505 Mg^{-1}, respectively. Seed and fertilizer costs were the largest contributor to the field production cost, while facility and labor costs were the highest contributors to processing costs. This analysis showed that hemp grain and fiber had high resource requirements but, with the current state of technology, could produce higher net income compared to conventional crops. However, due to the high price fluctuations, hemp production for grain and fiber also showed risks when considering low market product prices. In conclusion, under current conditions, hemp grain and fiber can provide U.S. farmers with a viable alternative crop that can be grown in rotation with existing crops such as corn, soybean and cotton.

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